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Parametric Study of Pipe Whip Analysis

R. C. Chun, T. Y. Chuang

Prepared for
U.S. Nuclear Regulatory Commission

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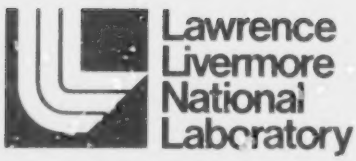

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ABSTRACT

In the Energy Balance Analysis Model (Standard Review Plan (USNRC, 1981), Section 3.6.2, "Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping,") time dependence is not considered, and a constant blowdown thrust force is assumed. This force includes an amplification factor of 1.1 to account for potential effects of rebound. Many of the assumptions used in establishing the acceptance criteria, as stated in the Standard Review Plan, were based on engineering judgement and logic intended to assure upper bound design rather than on a mechanistic assessment of actual pipe rupture phenomena and their effects. As a result of the current practice an exceedingly conservative design may be introduced.

This report represents a parametric study of the amplification factor to account for rebound effects in the Energy Balance Method. Of the 71 distinct cases we chose for our parametric study, the amplification factor of 1.1 seems sufficient except in five cases where the carbon steel pipes are small or have very small gaps between the pipes and the pipe whip restraints.

We conclude that the amplification factor generally decreases as the parameters gap size, hinge-to-break distance and overhang increase.

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NOMENCLATURE

A	Amplification factor
D_n	Nominal pipe diameter
D_o	Outer pipe diameter
E	Young's modulus of the pipe material
E1	Energy used in deforming U-bar
E2	Energy used in rotating pipe around plastic hinge
E_1	First slope used to discretize the stress-strain curve of the pipe material
E_2	Second slope used to discretize the stress-stain curve of the pipe material
E_3	Third slope used to discretize the stress-strain curve of the pipe material
F_{all}	Allowable U-bar force
F_R	U-bar force
F_y	U-bar force at yielding
H	Height of honeycomb restraint
I	Moment of inertia of the pipe cross-section
K	Thrust coefficient
L_1	Distance between pipe break and anchor
L_2	Overhang
L_3	Distance from the pipe break to the nearest butt weld of the elbow
L_4	Restraint-to-anchor distance
L_5	Distance from the pipe whip restraint to the nearest butt weld of the elbow

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L_{eff}	Effective length of a U-bar pipe whip restraint
L_h	Distance between pipe break and plastic hinge
M_{max}	Maximum moment at anchor
M_p	Plastic moment of the pipe
P	Force at cantilever tip
S	A factor defined as M_p/TL_2
S_m	Design stress intensity
T	Jet thrust force
a	Pipe thickness allowance for corrosion
d_{min}	Minimum required diameter of a U-bar pipe whip restraint
d_n	Nominal diameter of a U-bar pipe whip restraint
g_{eff}	Effective gap between pipe and U-bar pipe whip restraint
n	Number of U-bar restraint rods put next to one another
p	System pressure prior to pipe break
r_i	Inside radius of pipe
r_o	Outside radius of pipe
t_m	Minimum required wall thickness of pipe
t_n	Nominal wall thickness of pipe
u_{all}	Allowable U-bar displacement
u_R	U-bar displacement
u_y	U-bar displacement at yielding
y_{max}	Maximum displacement of cantilever
ε_{all}	Allowable strain of pipe whip restraint

ε_y	Yield strain of pipe whip restraint
σ_1	First stress level used in discretizing the stress-strain curve of the pipe material
s_2	Second stress level used in discretizing the stress-strain curve of the pipe material
σ_{all}	Allowable stress in U-bar
σ_{max}	Maximum stress in cantilever
σ_p	Stress level in pipe when a plastic hinge is formed
σ_y	Yield stress in U-bar pipe whip restraint

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1. EXECUTIVE SUMMARY

This report presents a parametric study of the amplification factor to account for rebound effects in the Energy Balance Method. To investigate the sufficiency of the amplification factor, we used WIPS, a special purpose, implicit, finite-element computer code for the structural analysis of pipe whip dynamic effects.

Nine parameters were identified for our study in 71 distinct cases, which are gathered and presented in a single figure (Fig. 13). Of the nine parameters, the gap size, hinge-to-break distance and overhang appear to have the most effect on the pipe whip restraint design. We conclude that the amplification factor generally decreases as the parameters gap size, hinge-to-break distance and overhang increase. (Figures 10 to 12).

In the cases of small carbon steel pipes with small gaps between the pipes and the pipe whip restraints, the amplification factor may be larger than the 1.1 as depicted in the Standard Review Plan, Section 3.6.2 [1]. Some of the ways these few cases can foreseeably be circumvented are by using an oversized pipe whip restraint or by increasing the gap size.

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1. BACKGROUND

General Design Criterion 4, "Environmental and Missile Design Bases," of Appendix A to 10CFR Part 50, "General Design Criteria for Nuclear Power Plants," requires that systems and components important to safety shall be protected against dynamic effects, including pipe rupture. Pipe whip restraints are usually installed to mitigate the dynamic effects on adjacent structures. Their appropriate locations are described in the Standard Review Plan (USNRC), Section 3.6.2 [1], "Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping," which also delineates acceptable models of analyses.

In one of the acceptable methods, namely the Energy Balance Analysis Model, time dependence is not considered, and a constant blowdown thrust force is assumed. This force includes an amplification factor of 1.1 to account for potential effects of rebound. Many of the assumptions used in establishing the acceptance criteria, as stated in the Standard Review Plan, were based on engineering judgement and logic intended to assure upper bound design rather than on a mechanistic assessment of actual pipe rupture phenomena and their effects. As a result of the current practice an exceedingly conservative design may be introduced.

To investigate the sufficiency of the amplification factor, we chose to use the computer code WIPS [2,3,4,5,6], which was developed by Professor G. H. Powell of the University of California at Berkeley under contract from the U.S. Nuclear Regulatory Commission (NRC) to the Lawrence Livermore National Laboratory (LLNL). WIPS is a special purpose, implicit, finite-element computer code for the structural analysis of pipe whip dynamic effects following a postulated pipe rupture in a nuclear power plant. The code can be used to determine: (1) the overall motions of a piping system, (2) the detailed deformations of individual piping components, and (3) the impact forces and local deformations at points of pipe-to-pipe or pipe-to-wall impact. Some of the features of WIPS are:

- Its curve pipe element can take the ovalling effect into consideration.
- Strain-rate effects can explicitly be included for all of its elements (beam, pipe, U-bar, gap-friction, and shell).
- Nonlinear kinematics includes large displacements and large strains, and material nonlinearities are represented by the Mroz plasticity model.

In our parametric study, we used only the pipe element and the U-bar element.

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2. PROJECT OBJECTIVE AND APPROACH

For each of the parameters we chose to study, our objective was to evaluate the validity of the amplification factor of 1.1. Our approach was to:

(1) Perform a dynamic analysis of the pipe whip event with the finite-element computer program WIPS.

(2) Determine the required amplification factor in the Energy Balance Method which will match the results of WIPS.

(3) Develop simplified charts, tables and/or equations that can be conveniently used in the licensing process for evaluating pipe whip restraint designs.

3. DESIGN CONSIDERATIONS

Before the results of our initial parametric study are presented, we will discuss some of the parameters of our pipe whip model:

3.1. Restraint Location

A long-radius elbow was assumed throughout our parametric study and the pipe whip restraint was placed as close to the elbow as practical. We assumed the restraint to be six inches away from the butt weld of the elbow (L_5 = 6", see Fig. 1), except in the case of the overhang parametric study where we varied L_5 from 0" to 18", and two cases of smaller pipe sizes (L_5 = 2.5" for 4" pipe, 4" for 8" pipe).

3.2. Restraint-to-Anchor Distance

Although the restraint-to-anchor distance (L_4) was not one of our parameters, we attempted to adopt a realistic value so that it would be close to an actual design based on elastic analyses. In other words, the pipe was assumed to be elastic when the pipe closed the gap in the pipe whip restraint. Assuming a cantilever beam between the anchor and the pipe whip restraint, the maximum displacement at the tip of the cantilever is:

$$y_{max} = \frac{PL_4^3}{3EI} = \frac{M_{max}L_4^2}{3EI} \qquad (1)$$

where

M_{max} = maximum moment at anchor = PL_4
P = force at cantilever tip

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E = Young's modulus of pipe material
I = moment of inertia of pipe cross-section.

We can rewrite equation (1) as,

$$M_{max} = \frac{3EI\, y_{max}}{L_4^2} \quad . \tag{2}$$

From the theory of elasticity,

$$M_{max} = \frac{\sigma_{max} I}{r_o} \tag{3}$$

where

σ_{max} = maximum stress

r_o = outside radius of pipe.

Equating (2) and (3), we can express the length of the cantilever beam as:

$$L_4 = \left(\frac{3Er_o y_{max}}{\sigma_{max}}\right)^{1/2} \quad .$$

In our selection of L_4 , we assumed

$E = 29 \times 10^6$ psi
$\sigma_{max} = 20{,}000$ psi .

Since $y_{max} = g_{eff}$ = effective gap [7] of the pipe whip restraint, we can write our expression for the cantilever as:

$$L_4 = 65.95\ (r_o\ g_{eff})^{1/2}$$

In our parametric study (except the case of honeycomb pipe whip restraint) we used a U-bar pipe whip restraint (see Fig. 2) manufactured by the Quadrex Corporation. (This is very similar to the restraints manufactured by the General Electric Company.) In a U-bar pipe whip restraint, the effective gap is defined as the distance the pipe must travel before the restraint becomes fully taut [7].

3.3. Pipe Thickness

From NB-3641.1 of the ASME Boiler and Pressure Vessel Code, Section III [8], the minimum thickness of a pipe wall required for design pressure is:

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$$t_m = \frac{p\, D_o}{2(S_m + 0.4p)} + a \qquad (4)$$

where

t_m = minimum required wall thickness in inches
D_o = outside diameter of the pipe, inches
S_m = design stress intensity
(See Table I-1.0, Appendix I of the Boiler and Pressure Vessel Code, Section III [8])
a = additional thickness for corrosion
(In our study, we used a = 0.0024" for stainless steel and 0.120" for carbon steel.)

In general design practice, a pipe schedule is selected such that the nominal thickness is $t_n \geq (8/7)\, t_m$.

3.4. Pipe Whip Restraint Design

For each case of our parametric study, an actual pipe whip restraint has to be designed so that a force-displacement relationship can be supplied to the WIPS analysis and the Energy Balance Analysis Model (USNRC, 1981).

3.4.1 U-bar Pipe Whip Restraint

The effective length of the U-bar pipe whip restraint is taken as 45". From this, we can determine the required diameter of our U-bar pipe whip restraint by using equation 10 presented in the Quadrex technical catalogue (Quadrex Corporation, 1978),

$$d_{min} = \left[\frac{4\, T\, (g_{eff} + L_{eff}\ \varepsilon_{all})}{\pi\, n\, L_{eff}(\sigma_y\, \varepsilon_{all} + \sigma_{all}\, (\varepsilon_{all} - \varepsilon_y))}\right]^{1/2} \qquad (5)$$

where

L_{eff} = effective length of restraint (defined [Quadrex Corporation, 1978] as the rod length which absorbs the kinetic energy of a pipe whip event by inelastic elongation)

n = number of restraint rods put next to one another (taken as unity in our parametric study)

ε_{all} = allowable strain = 0.255

ε_y = yield strain = 0.00132

σ_{all} = allowable stress = 70,500 psi

σ_y = yield stress = 38,000 psi

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T = jet thrust force = $Kp\pi r_i^2$

p = system pressure prior to pipe break

r_i = inside radius of pipe

K = thrust coefficient (1.26 for steam, saturated water, or steam-water mixtures, 2.0 for subcooled nonflashing water (USNRC, 1981)).

We next select a nominal diameter such that:

$$d_n \geq d_{min} \quad .$$

It follows that

u_{all} = allowable displacement of U-bar = $\varepsilon_{all} L_{eff}$

u_y = displacement of U-bar at yield point = $\varepsilon_y L_{eff}$

F_{all} = allowable force on the two rods of a U-bar (see Fig. 2)

$$= 2 \pi \left(\frac{d_n}{2}\right)^2 \sigma_{all}$$

F_y = force on U-bar at yield point = $2 \pi \left(\frac{d_n}{2}\right)^2 \sigma_y$.

Finally, the force-displacement relationship is represented bilinearly as in Fig. 3.

3.4.2 Honeycomb Pipe Whip Restraint

The Hexcel Corporation at Montebello, California provided us a series of experimental force-displacement curves performed on 4-inch cubes of steel honeycomb materials. The one we chose for our investigation had the following characteristics:

crush strength = 6,710 psi
rated energy dissipating capacity = 213,600 in-lb, and
displacement at yield point = 0.1".

The σ-ε data (Fig. 4) was then constructed according to the U.S. NRC Standard Review Plan (1981), Section 3.6.2, which states that "the allowable capacity of crushable material shall be limited to 80% of its rated energy dissipating capacity":

ε_y = yield strain = $\frac{0.1"}{4.0"}$ = 0.025

u_{all} = allowable displacement

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$$\approx \frac{0.8 \times 213{,}600 \text{ in-lb}}{(6{,}710 \text{ psi})\ (4")^2} = 1.6"$$

ε_{all} = allowable strain
= 1.6"/4"
= 0.4 .

In this particular parametric study, the pipe had an outside diameter of 16" and the honeycomb material cross-section was 16" x 4". The jet thrust force in this example was calculated to be 222.66 kips, and a gap (g) of 4.5" was used for installation. We determined the height (H) of the honeycomb pipe whip restraint (so that a force-displacement relationship was available for analyses) by approximating the maximum energy absorbed by the honeycomb material to the work done by the jet thrust force,

$$16" \times 4" \times (H \times \varepsilon_{all}) \times (6.710 \text{ ksi}) = (222.66 \text{ k})\ (g + H\ \varepsilon_{all})$$

$$16" \times 4" \times (H \times 0.4) \times (6.710 \text{ ksi}) = (222.66 \text{ k})\ (4.5" + 0.4\ H)$$

$$H = 12.11" .$$

Hence, we selected a height of 12.5" of honeycomb material (16" x 4" x 12.5"). Finally, the force-displacement relationship (see Fig. 5) was obtained as follows:

F_y = Force at yield point = (6.710ksi) (16" x 4") = 429.22 k

u_y = displacement at yield point = ε_y H = .025 x 12.5" = .3125"

u_{all} = allowable displacement = ε_{all} H = 0.4 x 12.5" = 5.0".

3.5 Stress-Strain Relationship for Pipe Materials

We chose SA376TP304 and SA106Gr.B to represent respectively the austenitic and carbon steels for our parametric study. Both of these are used commonly in the industry. As an approximation, we chose to linearize the stress-strain curves as shown in Fig. 6, where the values of Young's modulus (E's) and the stress levels (σ's) are listed in Table 1.

4. USE OF THE ENERGY BALANCE METHOD AND WIPS DYNAMIC ANALYSES TO ESTABLISH THE AMPLIFICATION FACTOR TO ACCOUNT FOR REBOUND EFFECTS

The hinge-to-break distance (L_h) [9], can be expressed as:

$$L_h = 1.5 \left(\frac{M_p}{T}\right) \left[1 + \sqrt{1 + \frac{8}{3} \left(\frac{L_3}{M_p/T}\right)}\right] \qquad (6)$$

where

M_p = plastic moment of the pipe = $\frac{4}{3}(r_o^3 - r_i^3)\ \sigma_p$ (7)

T = jet thrust force = $Kp\pi r_i^2$ (8)

p = system pressure prior to pipe break
r_o = outside radius of pipe
r_i = inside radius of pipe
σ_p = stress level when plastic hinge occurs
K = thrust coefficient (1.26 for steam, saturated water, or steam-water mixtures, 2.0 for subcooled nonflashing water [1]
L_3 = distance from the pipe break to the nearest butt weld of the elbow.

In our study, we varied L_3 (from 0" to 36") to obtain different hinge-to-break distances.

From a WIPS dynamic pipe whip analysis, we knew the maximum displacement (u_R) and the maximum force (F_R) on the pipe whip restraint. Therefore, from Fig. 3

E1 = energy in deforming U-bar
= $1/2\ F_y u_y + 1/2(F_y + F_R)(u_R - u_y)$

E2 = energy in rotating pipe around plastic hinge

= $M_p \tan^{-1}\left(\frac{g_{eff} + u_R}{L_h - L_2}\right)$ (see Fig. 7)

W = work done by the jet thrust force

= $(A)\ (T)\ (g_{eff} + u_R)\ \left(\frac{L_h}{L_h - L_2}\right)$

where

T = jet thrust force
A = amplification factor (to establish the magnitude of the forcing function in order to determine the maximum reaction force of the restraint beyond the first quarter cycle of response).

Equating the work done by the jet thrust force to the energy spent in deforming the U-bar and in rotating the pipe around the plastic hinge,

$$W = E1 + E2, \quad (9)$$

we determined the amplification factor, A.*

---

*It should be noted that the amplification factor A is to be applied at the pipe break and not at the pipe whip restraint. Thus a larger amplification factor does not necessarily mean a larger pipe whip restraint is required.

5. PARAMETRIC STUDY

The following nine parameters were studied in this project:

1. pressure
2. pipe size
3. gap size
4. hinge-to-break distance
5. overhang
6. pipe material
7. temperature
8. fluid type
9. restraint type.

These parameters were selected because we believe they are the most important ones in designing pipe whip restraints. Although we recognize that some of these parameters may not be as important as the others, we have included all of them for completeness.

As discussed in Section 3.5, we selected two types of pipe materials, namely SA376TP304 and SA106Gr.B, to represent austenitic stainless steels and carbon steels. The austenitic stainless steel was studied in detail at 400°F and 600°F, whereas the carbon steel was studied in detail at 300°F and 546°F. (These are the 'medium' and 'high' temperatures for which we have the stress-strain curves.) For each of the four combinations of pipe material and temperature, the effects of the first five parameters (pressure, pipe size, gap size, hinge-to-break distance, and overhang) were investigated (see Tables 2 to 5). All of the above analyses assumed a U-bar restraint and a steam or water-steam mixture system (i.e., k = 1.26). For the eighth parameter (fluid type), two cases of a water system (k = 2.00) and two cases of a steam system were studied (see Table 6). For the ninth parameter (restraint type) one case of honeycomb pipe whip restraint and one case of U-bar pipe whip restraint were investigated (see Table 7).

6. RESULTS AND CONCLUSIONS

The results of our parametric study are listed in Tables 2 to 7. These results are rearranged and presented in graphical forms in Figures 8 to 12.

From Figures 8 and 9, no definite trends can be established between the amplification factor and the parameters pressure and pipe diameter. From Figures 10 to 12, we observe that for a given pipe material at a given temperature the amplification factor generally decreases as the parameters gap size, hinge-to-break distance and overhang increase. Of the nine parameters we used in our study, these three parameters appear to have the most effect on the pipe whip restraint design.

Table 6 indicates that the amplification factors go down from 1.14 and 1.04 to 1.08 and 0.86, respectively, when the fluid type changes from steam to water. Table 7 shows that the amplification factor goes down slightly from 0.88 to 0.84 when the restraint type changes from a steel U-bar to a honeycomb restraint.

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Of all the cases we investigated, the amplification factors are larger than 1.1 in only seven cases. These cases are listed in Table 8, and deserve a more careful examination:

1. All seven cases are of material type SA106Gr.B. For the carbon steel, a large thickness allowance for corrosion (a = 0.120") was used in this study. For all the stainless steel cases (a = 0.0024"), the amplification factors are below 1.1.

2. Case C3.2 and C3.3 have very small effective gaps of 0.75" and 1.5". The amplification factor will be below 1.1 for larger gaps. Case C3.1 is an unrealistic case because the effective gap can never be zero.

3. Case C5.1 represents a case of $L_5 = 0$. In reality, the restraints are normally designed to be at a certain distance from the butt weld of the elbow (i.e., $L_5 > 0$).

4. Cases C2.1, C2.2 and D2.1 are of smaller pipes (4" and 8"). All pipes equal to or larger than 16" in our study have amplification factors below 1.1.

All of our analyses assume an efficient design has been made according to Section 3.4. To study the possible effect of an over-design, we arbitrarily increased the diameter of the restraint in Case C3.2 from 1.75" to 2.5". We observed that the amplification factor decreased from 1.21 to 1.00 in this case. In other words, an oversized pipe whip restraint can reduce the amplification factor.

Finally, it is interesting to point out that the amplification factor (Figures 8 to 12) drops lower at a higher temperature for the carbon steel. However, no such trend appears for the stainless steel. This is possibly due to the much larger corrosion allowance we used for the carbon steel (a=0.120" compared to 0.0024" for the stainless steel).

In summary, of the 71 distinct cases we chose for our parametric study, the amplification factor of 1.1 seems sufficient except in five cases (after deleting the unrealistic cases C3.1 and C5.1) where the carbon steel pipes are small or have very small gaps between the pipes and the pipe whip restraints. However, for these five cases, the amplification factor can be reduced by increasing the gap size, hinge-to-break distance, overhang, or the size of the pipe whip restraint.

All of our results can be gathered in a single figure (Fig. 13) if we define a new variable S as:

$$S = \frac{M_p}{TL_2} . \qquad (10)$$

Note that in a reasonable design, S should always be greater than unity, otherwise a plastic hinge will occur between the pipe break and the pipe whip restraint, thus defeating the purpose of the restraint. This means that the

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distance between the pipe whip restraint and the pipe break (L_2) should be less than M_p/T.

We conclude that the following equation can be used as an envelope for the amplification factor:

$$A = \begin{cases} 0.4828(S) + 0.4 , & 1.00 < S < 1.68 \\ 1.21 , & S \geq 1.68 \end{cases} \quad (11)$$

7. FIGURES

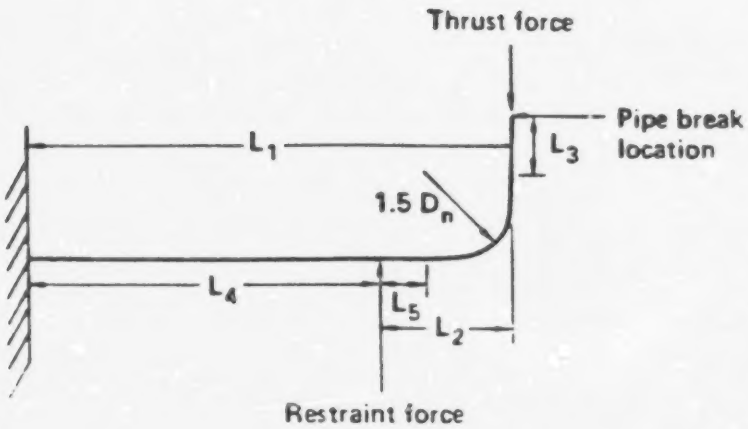

Figure 1. Model for Pipe Whip Parametric Study

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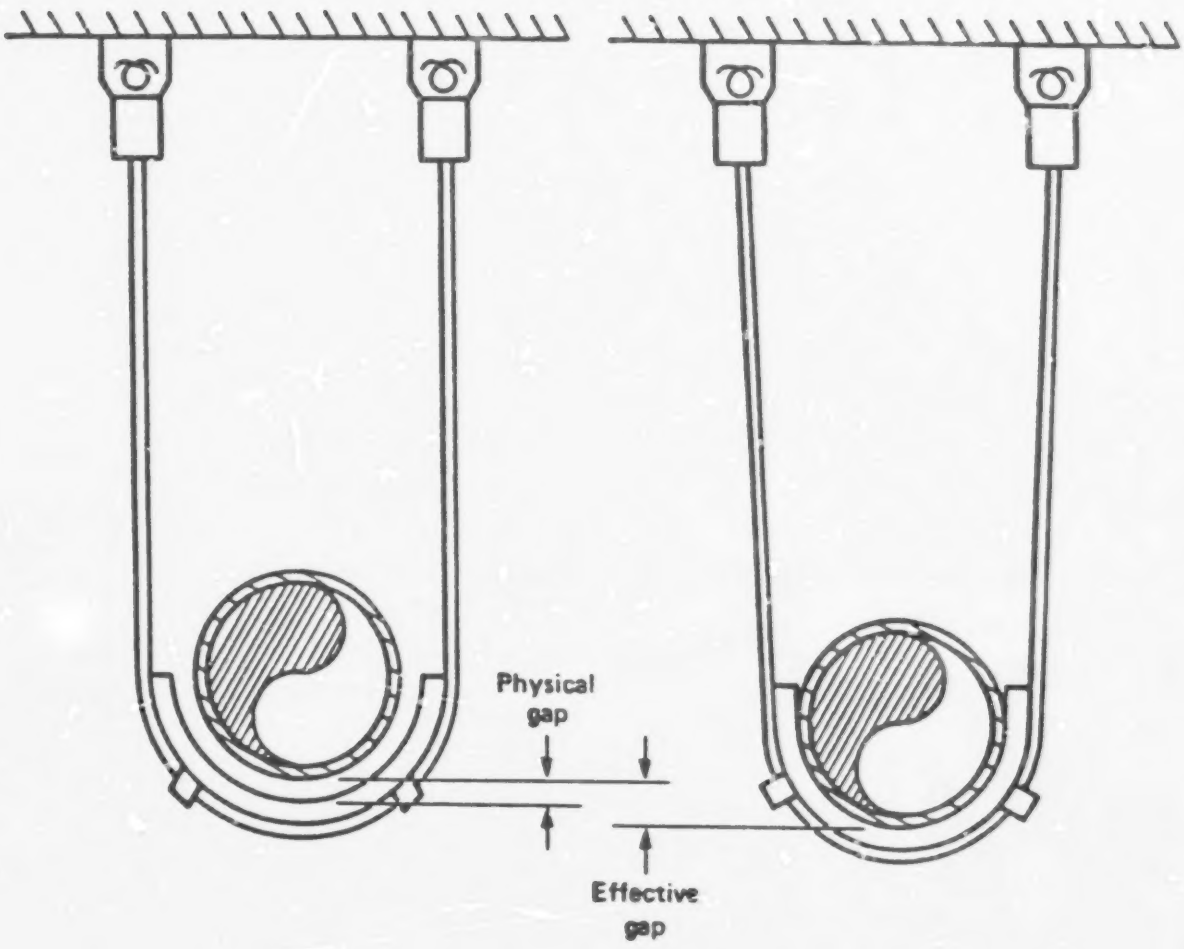

Figure 2. U-Bar Pipe Whip Restraint

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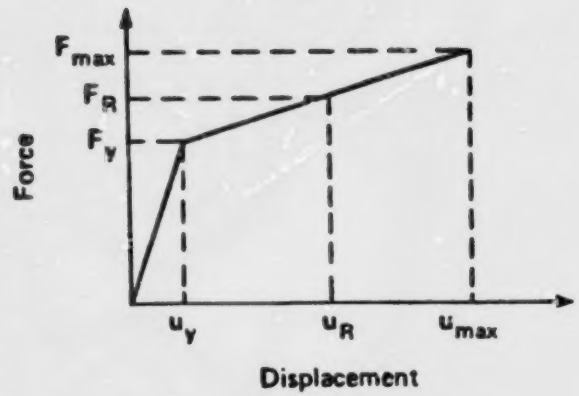

Figure 3. Force-Displacement Relationship of U-Bar Pipe Whip Restraint

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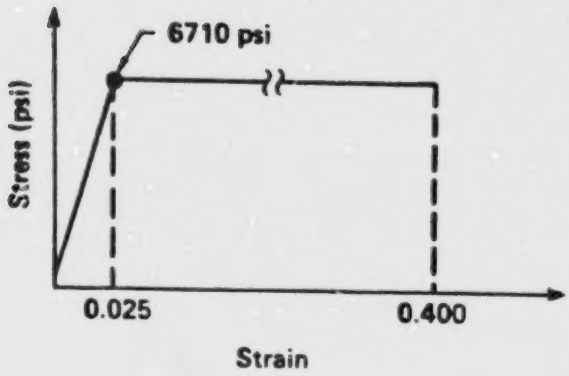

Figure 4. Stress-Strain Curve of Sample Honeycomb Material

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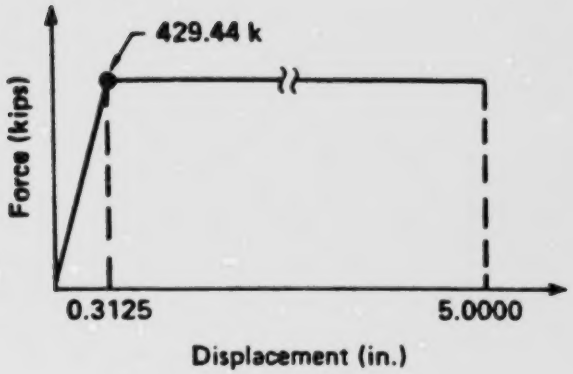

Figure 5. Force-Displacement Relationship of Sample Honeycomb Pipe Whip Restraint

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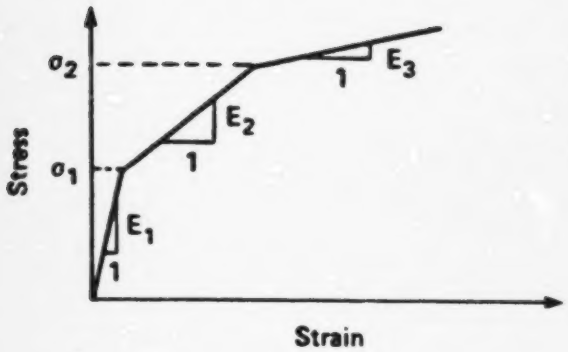

Figure 6. Stress-Strain Representation of Pipe Materials

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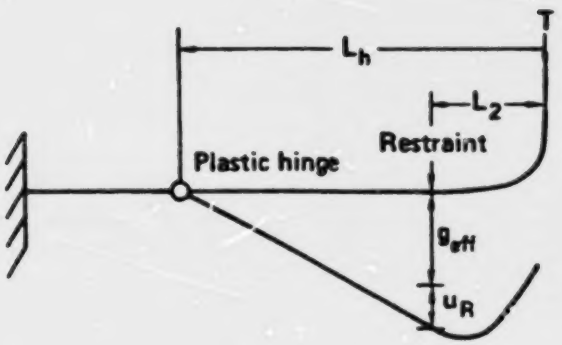

Figure 7. Illustration of Plastic Hinge

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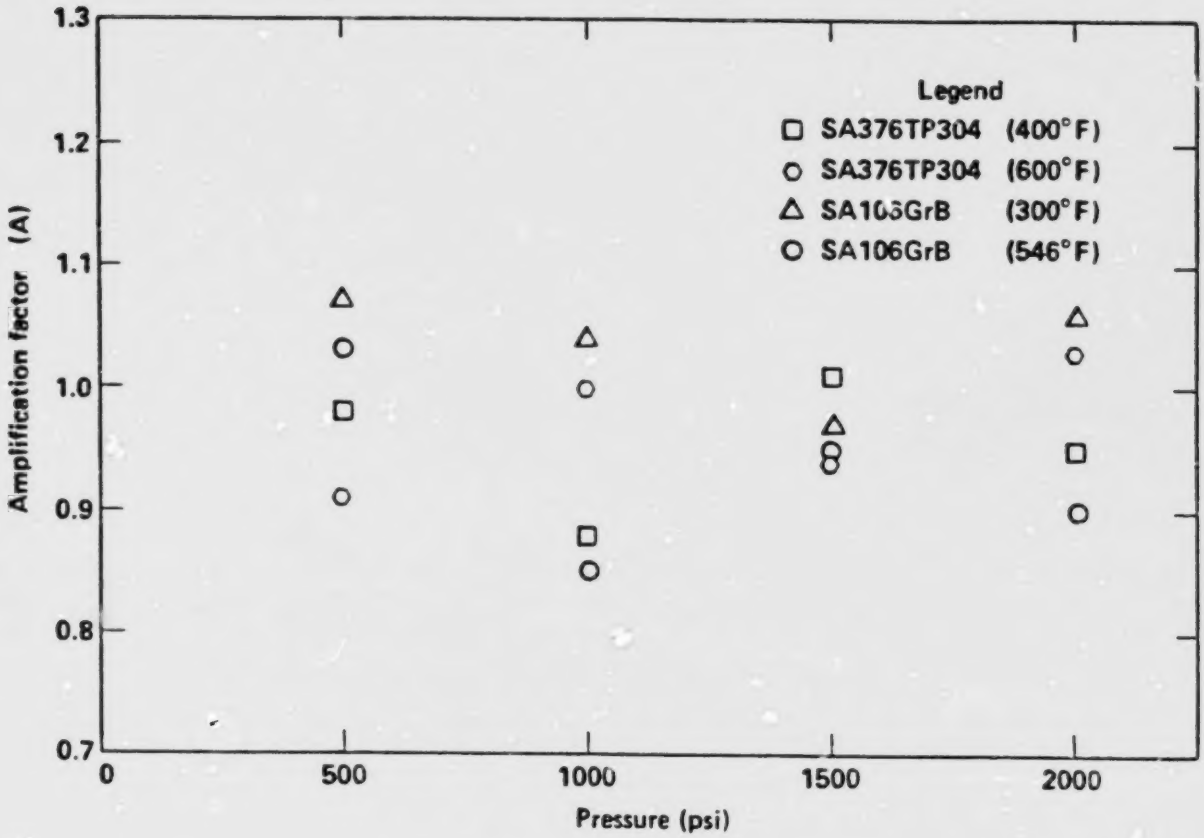

Figure 8. Amplification Factor vs Pressure

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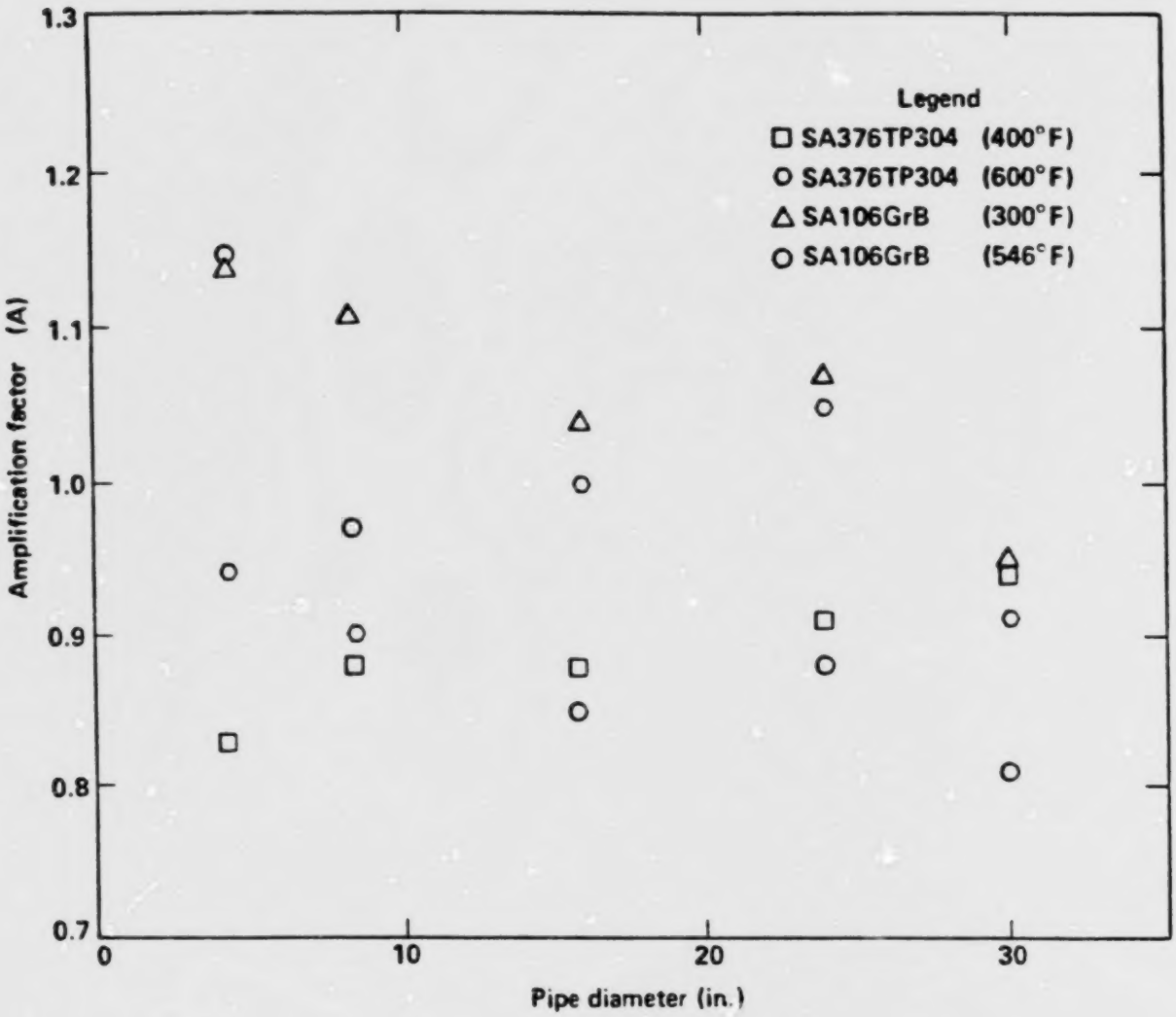

Figure 9. Amplification Factor vs Pipe Diameter

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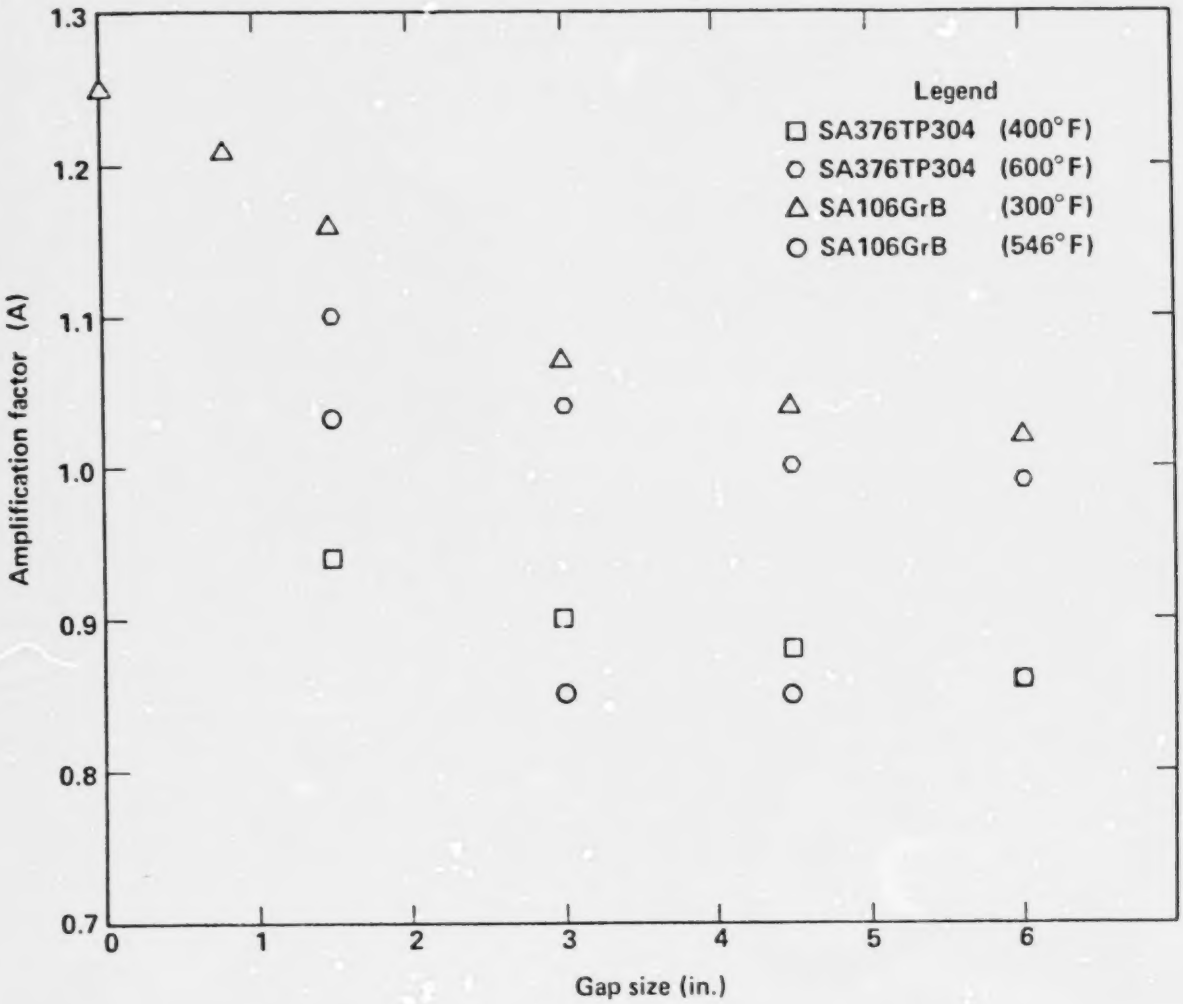

Figure 10. Amplification Factor vs Gap Size

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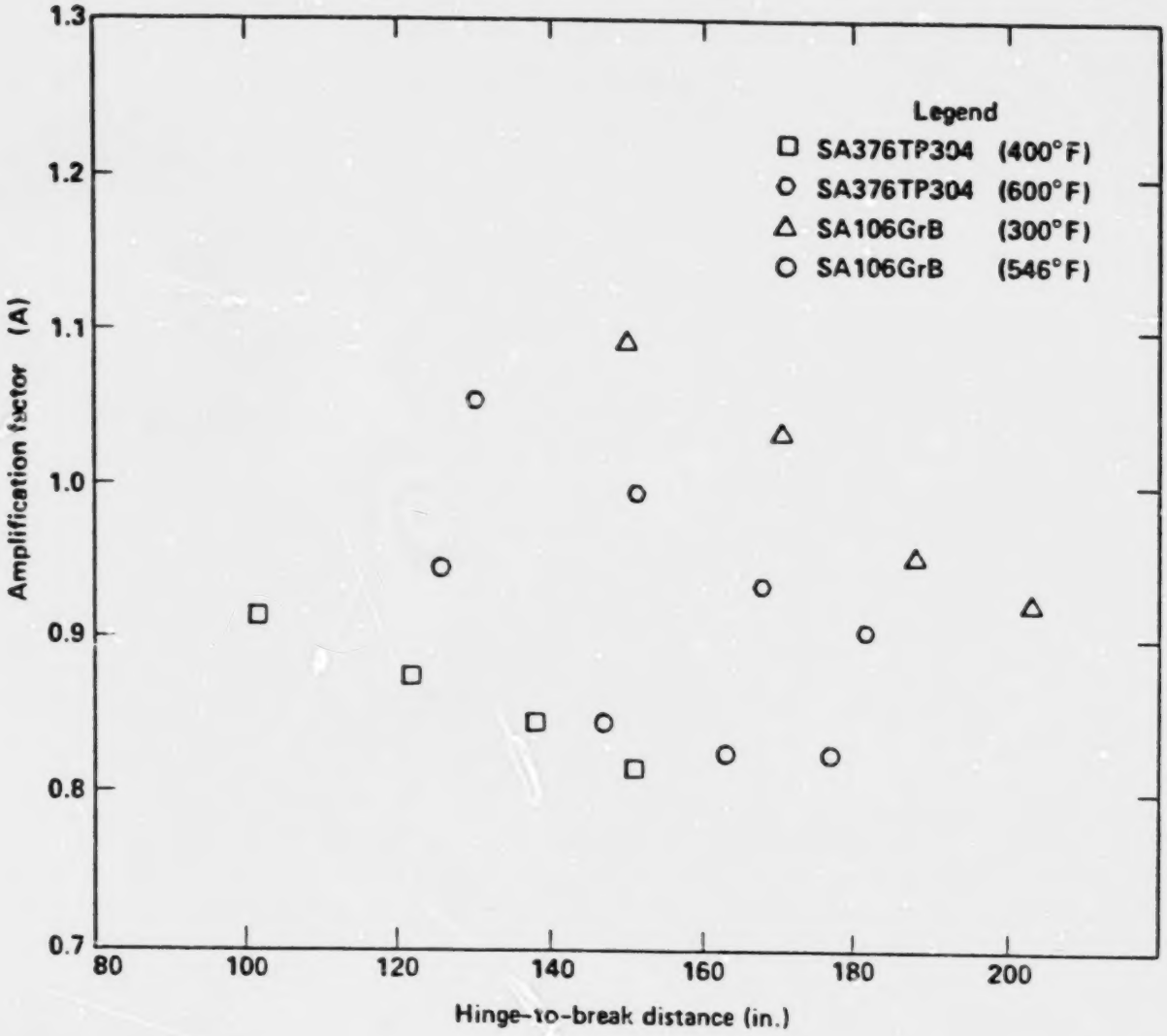

Figure 11. Amplification Factor vs Hinge-to-Break Distance

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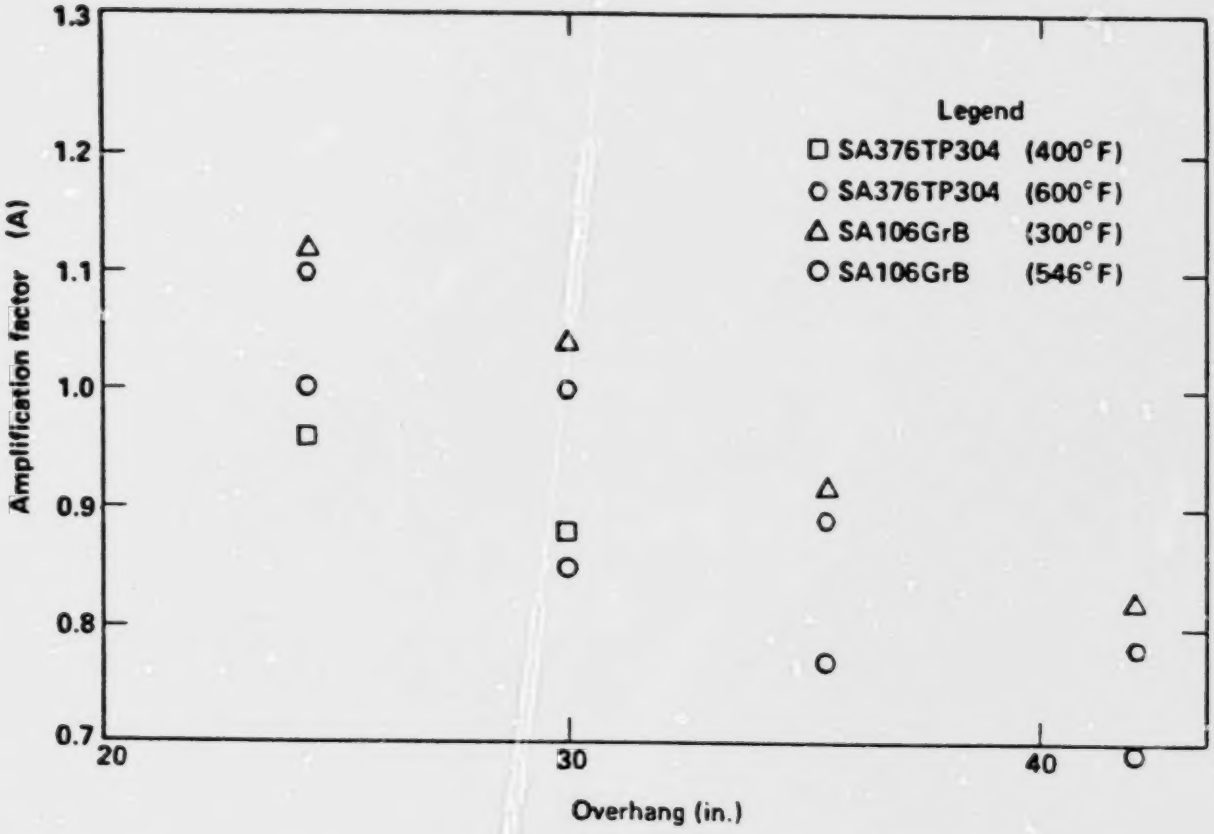

Figure 12. Amplification Factor vs Overhang

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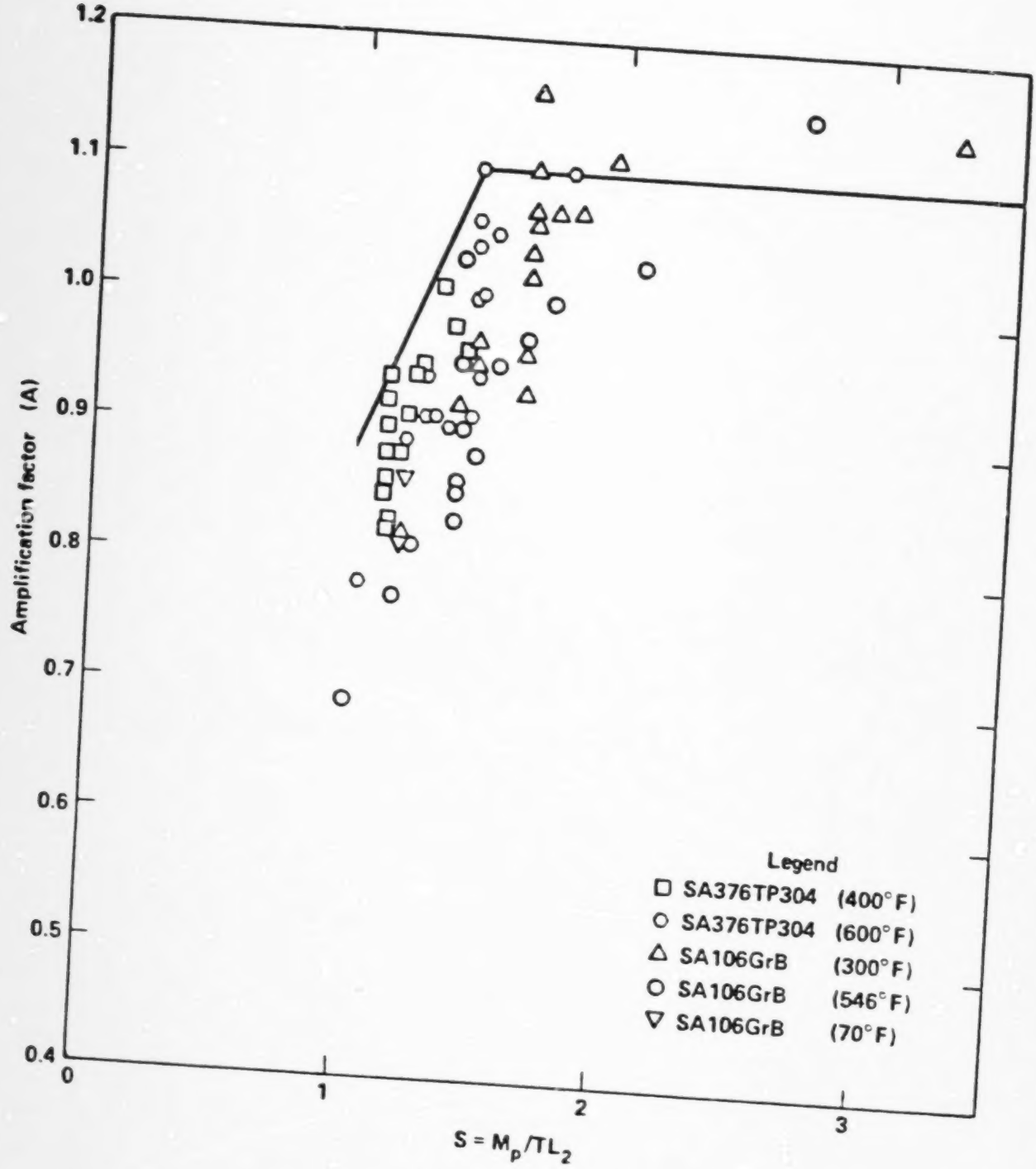

Figure 13. Amplification Factor vs S Factor

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Table 1. Trilinear Stress-Strain Representation for Selected Stainless and Carbon Steels

Type	Temperature (°F)	E_1 (ksi)	E_2 (ksi)	E_3 (ksi)	σ_1 (ksi)	σ_2 (ksi)
SA376TP304	70	11,000	47.06	0.01	55	83
	400	10,000	32.91	0.01	50	63
	600	8,600	47.09	0.01	43	60
SA106Gr.B	70	10,000	128.89	0.01	50	79
	300	8,200	124.44	0.01	41	69
	546	6,000	119.15	0.01	30	58

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Table 2 - Amplification Factors for SA376TP304 Pipes at 400° F

Case	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
A1.1	500.	16.	0.312	430.	30.	12.	1.50	4.5	1.26	1.38	0.98
A1.2	1000.	16.	0.500	430.	30.	12.	2.00	4.5	1.26	1.13	0.88
A1.3	1500.	16.	0.843	430.	30.	12.	2.25	4.5	1.26	1.34	1.01
A1.4	2000.	16.	1.031	430.	30	12.	2.75	4.5	1.26	1.26	0.95
A2.1	1000.	4.5	0.142	220.	8.5	12.	0.625	4.5	1.26	1.14	0.83
A2.2	1000.	8.625	0.277	310.	16.	12.	1.25	4.5	1.26	1.18	0.88
A2.3	1000.	16.	0.500	430.	30.	12.	2.00	4.5	1.26	1.13	0.88
A2.4	1000.	24.	0.750	530.	42.	12.	3.00	4.5	1.26	1.21	0.91
A2.5	1000.	30.	0.938	595.	51.	12.	3.75	4.5	1.26	1.25	0.94
A3.1	1000.	16.	0.500	260.	30.	12.	1.75	1.5	1.26	1.13	0.94
A3.2	1000.	16.	0.500	355.	30.	12.	2.00	3.0	1.26	1.13	0.90
A3.3	1000.	16.	0.500	430.	30.	12.	2.00	4.5	1.26	1.13	0.88
A3.4	1000.	16.	0.500	490.	30.	12.	2.00	6.0	1.26	1.13	0.86
A4.1	1000.	16.	0.500	430.	30.	0.	2.00	4.5	1.26	1.13	0.92
A4.2	1000.	16.	0.500.	430.	30.	12.	2.00	4.5	1.26	1.13	0.88
A4.3	1000.	16.	0.500.	430.	30.	24.	2.00	4.5	1.26	1.13	0.85
A4.4	1000.	16.	0.500	430.	30.	36.	2.00	4.5	1.26	1.13	0.82
A5.1	1000.	16.	0.500	420.	24.	12.	2.00	4.5	1.26	1.42	0.96
A5.2	1000.	16.	0.500	430.	30.	12.	2.00	4.5	1.26	1.13	0.88

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Table 3 - Amplification Factors for SA376TP304 Pipes at 600° F

Case	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
B1.1	500.	16.	0.312	430.	30.	12.	1.50	4.5	1.26	1.31	0.91
B1.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.45	1.00
B1.3	1500.	16.	0.843	430.	30.	12.	2.25	4.5	1.26	1.27	0.94
B1.4	2000.	16.	1.218	430.	30	12.	2.50	4.5	1.26	1.47	1.03
B2.1	1000.	4.5	0.188	220.	8.5	12.	0.75	4.5	1.26	1.47	0.94
B2.2	1000.	8.625	0.322	310.	16.	12.	1.25	4.5	1.26	1.36	0.90
B2.3	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.45	1.00
B2.4	1000.	24.	0.968	530.	42.	12.	3.00	4.5	1.26	1.52	1.05
B2.5	1000.	30.	1.000	595.	51.	12.	3.75	4.5	1.26	1.28	0.91
B3.1	1000.	16.	0.656	260.	30.	12.	1.75	1.5	1.26	1.45	1.10
B3.2	1000.	16.	0.656	355.	30.	12.	2.00	3.0	1.26	1.45	1.04
B3.3	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.45	1.00
B3.4	1000.	16.	0.656	490.	30.	12.	2.00	6.0	1.26	1.45	0.99
B4.1	1000.	16.	0.656	430.	30.	0.	2.00	4.5	1.26	1.45	1.06
B4.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.45	1.00
B4.3	1000.	16.	0.656	430.	30.	24.	2.00	4.5	1.26	1.45	0.94
B4.4	1000.	16.	0.656	430.	30.	36.	2.00	4.5	1.26	1.45	0.91
B5.1	1000.	16.	0.656	420.	24.	12.	2.00	4.5	1.26	1.81	1.10
B5.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.45	1.00
B5.3	1000.	16.	0.656	435.	36.	12.	2.00	4.5	1.26	1.21	0.89
B5.4	1000.	16.	0.656	440.	42.	12.	2.00	4.5	1.26	1.04	0.78

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Table 4 - Amplification Factors for SA106Gr.B Pipes at 300° F

Case	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
C1.1	500.	16.	0.375	430.	30.	12.	1.50	4.5	1.26	1.83	1.07
C1.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.66	1.04
C1.3	1500.	16.	0.843	430.	30.	12.	2.25	4.5	1.26	1.47	0.97
C1.4	2000.	16.	1.218	430.	30	12.	2.75	4.5	1.26	1.68	1.06
C2.1	1000.	4.5	0.337	220.	8.5	12.	0.50	4.5	1.26	3.28	1.14
C2.2	1000.	8.625	0.406	310.	16.	12.	1.00	4.5	1.26	1.96	1.11
C2.3	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.66	1.04
C2.4	1000.	24.	0.968	530.	42.	12.	3.00	4.5	1.26	1.75	1.07
C2.5	1000.	30.	1.000	595.	51.	12.	3.75	4.5	1.26	1.47	0.95
C3.1	1000.	16.	0.656	195.	30.	12.	1.75	0.	1.26	1.66	1.26
C3.2	1000.	16.	0.656	195.	30.	12.	1.75	0.75	1.26	1.66	1.21
C3.3	1000.	16.	0.656	260.	30.	12.	1.75	1.5	1.26	1.66	1.16
C3.4	1000.	16.	0.656	355.	30.	12.	2.00	3.0	1.26	1.66	1.07
C3.5	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.66	1.04
C3.6	1000.	16.	0.656	490.	30.	12.	2.00	6.0	1.26	1.66	1.02
C4.1	1000.	16.	0.656	430.	30.	0.	2.00	4.5	1.26	1.66	1.10
C4.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.66	1.04
C4.3	1000.	16.	0.656	430.	30.	24.	2.00	4.5	1.26	1.66	0.96
C4.4	1000.	16.	0.656	430.	30.	36.	2.00	4.5	1.26	1.66	0.93

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Table 4 - Amplification Factors for SA106Gr.B Pipes at 300° F
(Continued)

Case	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
C5.1	1000.	16.	0.656	420.	24.	12.	2.00	4.5	1.26	2.08	1.12
C5.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.66	1.04
C5.3	1000.	16.	0.656	435.	36.	12.	2.00	4.5	1.26	1.39	0.92
C5.4	1000.	16.	0.656	440.	42.	12.	2.00	4.5	1.26	1.19	0.82

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Table 5 - Amplification Factors for SA106Gr.B Pipes at 546° F

Case	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
D1.1	500.	16.	0.500	430.	30.	12.	1.50	4.5	1.26	2.09	1.03
D1.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.40	0.85
D1.3	1500.	16.	1.031	430.	30.	12.	2.25	4.5	1.26	1.55	0.95
D1.4	2000.	16.	1.218	430.	30	12.	2.50	4.5	1.26	1.42	0.90
D2.1	1000.	4.5	0.337	220.	8.5	12.	0.50	4.5	1.26	2.71	1.15
D2.2	1000.	8.625	0.406	310.	16.	12.	1.00	4.5	1.26	1.65	0.97
D2.3	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.40	0.85
D2.4	1000.	24.	0.968	530.	42.	12.	3.00	4.5	1.26	1.47	0.88
D2.5	1000.	30.	1.000	595.	51.	12.	3.75	4.5	1.26	1.23	0.81
D3.1	1000.	16.	0.656	260.	30.	12.	1.75	1.5	1.26	1.40	1.03
D3.2	1000.	16.	0.656	355.	30.	12.	2.00	3.0	1.26	1.40	0.85
D3.3	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.40	0.85
D3.4	1000.	16.	0.656	490.	30.	12.	2.00	6.0	1.26	1.40	0.86
D4.1	1000.	16.	0.656	430.	30.	0.	2.00	4.5	1.26	1.40	0.95
D4.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.40	0.85
D4.3	1000.	16.	0.656	430.	30.	24.	2.00	4.5	1.26	1.40	0.83
D4.4	1000.	16.	0.656	430.	30.	36.	2.00	4.5	1.26	1.40	0.83
D5.1	1000.	16.	0.656	420.	24.	12.	2.00	4.5	1.26	1.75	1.00
D5.2	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.40	0.85
D5.3	1000.	16.	0.656	435.	36.	12.	2.00	4.5	1.26	1.17	0.77
D5.4	1000.	16.	0.656	440.	42.	12.	2.00	4.5	1.26	1.00	0.69

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Table 6 - Amplification Factors for SA106Gr.B Pipes with Different Types of Fluid

Case	Temp (^{O}F)	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
E1.1	300	1000.	4.5	0.337	220.	8.5	12.	0.50	4.5	1.26	3.28	1.14
E1.2	70	1000.	4.5	0.337	220.	8.5	12.	0.75	4.5	2.00	2.37	1.08
E1.3	300	1000.	16.	0.656	430.	30.	12.	2.00	4.5	1.26	1.66	1.04
E1.4	70	1000.	16.	0.656	430.	30	12.	2.50	4.5	2.00	1.20	0.86

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Table 7 - Amplification Factors for SA376TP304 Pipes with Different Types of Pipe Whip Restraints

Case	Temp (^{o}F)	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	Restraint Dimensions	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
F1.1	400	1000.	16.	0.500	430.	30.	12.	U-bar 45"x2" diam	4.5	1.26	1.13	0.88
F1.2	400	1000.	16.	0.500	430.	30.	12.	Honeycomb 16"x4"x12.5"	4.5	1.26	1.13	0.84

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Table 8 - Cases Where the Amplification Factors are Larger than 1.1

Case	Mat'l	Temp (^{o}F)	P (psi)	Pipe Diam. (inch)	Pipe Th. (inch)	L_1 (inch)	L_2 (inch)	L_3 (inch)	U-bar diam. (inch)	G_{eff} (inch)	Thrust coeff. k	S Factor	Amplification Factor A
C2.1	SA106Gr.B	300	1000.	4.5	0.337	220.	8.5	12.	0.50	4.5	1.26	3.28	1.14
C2.2	SA106Gr.B	300	1000.	8.625	0.406	310.	16.	12.	1.00	4.5	1.26	1.96	1.11
C3.1	SA106Gr.B	300	1000.	16.	0.656	195.	30.	12.	1.75	0.	1.26	1.66	1.26
C3.2	SA106Gr.B	300	1000.	16.	0.656	195.	30.	12.	1.75	0.75	1.26	1.66	1.21
C3.3	SA106Gr.B	300	1000.	16.	0.656	260.	30.	12.	1.75	1.5	1.26	1.66	1.16
C5.1	SA106Gr.B	300	1000.	16.	0.656	420.	24.	12.	2.00	4.5	1.26	2.08	1.12
D2.1	SA106Gr.B	546	1000.	4.5	0.337	220.	8.5	12.	0.50	4.5	1.26	2.71	1.15

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9. REFERENCES

1. U. S. Nuclear Regulatory Commission, "Standard Review Plan, Section 3.6.2: "Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping", (Rev. 1, July 1981).

2. Powell, G. H., "WIPS - Computer Code for Whip and Impact Analysis of Piping Systems: Summary Report," NUREG/CR-3686, UCRL-15597, Summary (June 1984).

3. Powell, G. H., Hollings, J. P., Row, D. G., Chen, P., HU, F-C, Mahasuverachai, M., Mosaddad, B., Nicklin, P. Nour-Omid, S., Ougbourlian, C., and Riabi, A., "WIPS - Computer Code for Whip and Impact Analysis of Piping Systems: Part A, User's Manual," NUREG/CR-3686, UCRL-15597, Vol. 1 (June 1984).

4. Powell, G. H., Hollings, J. P., Row, D. G., Chen, P., HU, F-C, Mahasuverachai, M., Mosaddad, B., Nicklin, P. Nour-Omid, S., Ougbourlian, C., and Riabi, A., "WIPS - Computer Code for Whip and Impact Analysis of Piping Systems: Part B, Theory Manual," NUREG/CR-3686, UCRL-15597, Vol. 2 (June 1984).

5. Powell, G. H., Hollings, J. P., Row, D. G., Chen, P., HU, F-C, Mahasuverachai, M., Mosaddad, B., Nicklin, P. Nour-Omid, S., Ougbourlian, C., and Riabi, A., "WIPS - Computer Code for Whip and Impact Analysis of Piping Systems: Part C, Programmer's Manual," NUREG/CR-3686, UCRL-15597, Vol. 3 (June 1984).

6. Powell, G. H., Hollings, J. P., Row, D. G., Chen, P., HU, F-C, Mahasuverachai, M., Mosaddad, B., Nicklin, P. Nour-Omid, S., Ougbourlian, C., and Riabi, A., "WIPS - Computer Code for Whip and Impact Analysis of Piping Systems: Part D, Verification Manual," NUREG/CR-3686, UCRL-15597, Vol. 4 (June 1984).

7. Quadrex Corporation, Campbell, California, "WR78™ Pipe Whip Restraints Technical Catalogue," (1978).

8. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, "Section III--Rules for Construction of Nuclear Power Plant Components, Division 1, Subsection NB, Class 1 Components," (July 1, 1983).

9. Roemer, R. E.and East, G. H., "Prediction of Large Deformation Pipe Whip and Barrier Impact: A simplified Approach," ASME Publication No. 80-C2/PVP-48 (August 1980).

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13 ABSTRACT (200 words or less)

In the Energy Balance Analysis Model (Standard Review Plan (USNRC, 1981), Section 3.6.2, "Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping,") time dependence is not considered, and a constant blowdown thrust force is assumed. This force includes an amplification factor of 1.1 to account for potential effects of rebound. Many of the assumptions used in establishing the acceptance criteria, as stated in the Standard Review Plan, were based on engineering judgement and logic intended to assure upper bound design rather than on a mechanistic assessment of actual pipe rupture phenomena and their effects. As a result of the current practice an exceedingly conservative design may be introduced.

This report represents a parametric study of the amplification factor to account for rebound effects in the Energy Balance Method. Of the 71 distinct cases we chose for our parametric study, the amplification factor of 1.1 seems sufficient except in five cases where the carbon steel pipes are small or have very small gaps between the pipes and the pipe whip restraints.

We conclude that the amplification factor generally decreases as the parameters gap size, hinge-to-break distance and overhang increase.

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